ENHANCEMENTS OF GEOPHYSICAL MODELS FOR MONITORING

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ABSTRACT

Geophysical models constitute an important component of calibration for nuclear explosion monitoring. In order to keep them relevant to current monitoring problems, we have enhanced the models in several different ways. We will focus on discussing several of the enhancements here. We have significantly improved upon our surface wave model by expanding the region of the existing model of Eurasia and North Africa, south to cover all of Africa and north to cover the polar region into Alaska and Canada. We have also improved on our coverage in existing regions by including station-station dispersion paths based on ambient seismic noise. Surface waves are also being used to derive the crust and upper mantle velocity structure of these regions, including important parameters such as crustal thickness, upper mantle velocity, and lithospheric thickness. We will be comparing some of these results to other estimates of these parameters. We demonstrate some of the latest enhancements that we have made regarding stochastic models. For instance, we have been using the Markov Chain Monte Carlo (MCMC) technique to produce stochastic models in the Yellow Sea – Korean Peninsula (YSKP) region. By including more data sets (Love wave dispersion curves, gravity) and more data from the existing data sets (more travel times, more receiver functions, more Rayleigh wave dispersion curves), we have improved the lateral resolution of the model from 2 degrees to 1 degree. We will discuss some details of the methodology as well as features of the model. Finally, we will focus the last section on research to move beyond past and current 1-D, 2-D, and 2½-D methods and discuss some of the ongoing efforts to transition to fully 3-D models.

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OBJECTIVE

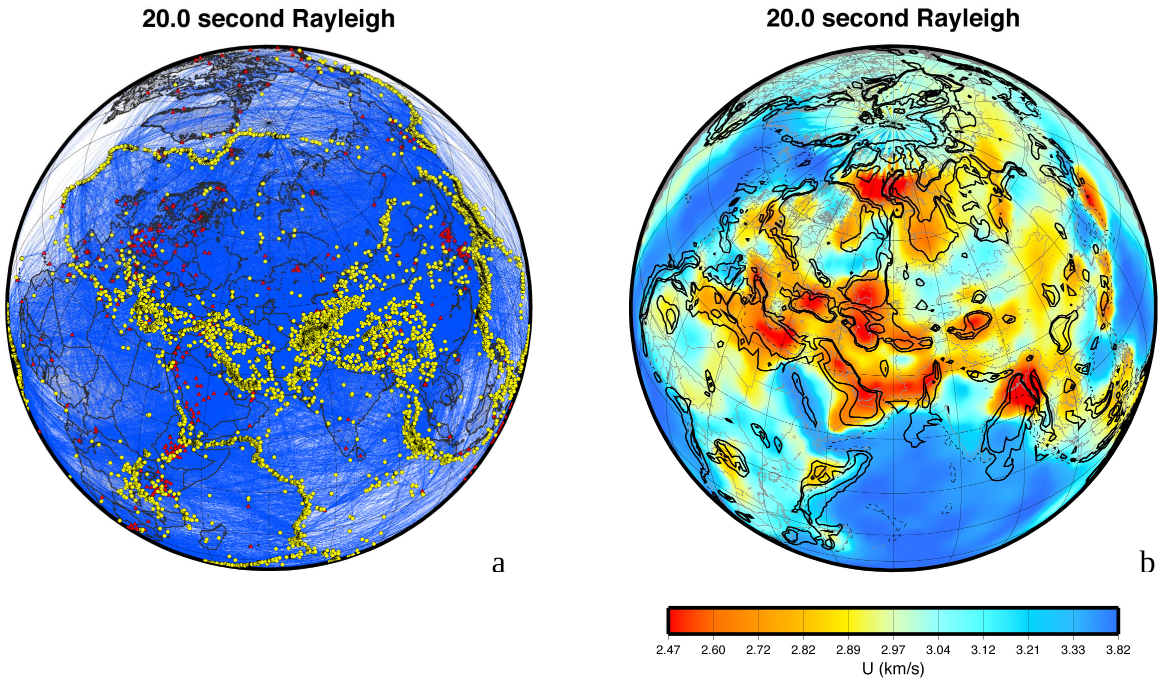
Geophysical models constitute an important component of calibration for nuclear explosion monitoring. The objective of any geophysical model is to improve prediction of travel times, amplitudes, and other observables of local, regional, and teleseismic phases, in order to improve location, detection, association, identification and (in the event of an explosion) yield determination. In this paper, we will focus on recent enhancements to many of the models, which have kept them up to date and relevant for current monitoring problems. We first discuss improvements to the surface wave models which have expanded to cover over half of the globe and have increased in resolution due to the increase in measurements and available seismic data, as well as techniques such as ambient noise correlation that allow us to sample new paths. Tomographic images over a wide period range are robust and reliable enough to allow the inversion of highly developed models that cover both shallow sediment structure and deep lithospheric models, even in aseismic regions. The results can also be focused on regional or station-specific applications. Geophysical models such as the Western Eurasia and North Africa (WENA) model can be updated to reflect our increased understanding of regions. They continue to both be useful in their own right, and also serve as critical starting models for more data driven models, such as the Seismic Location Baseline Model (SLBM) (Myers et al., these Proceedings). Finally, stochastic models, which require the most sophisticated inversion technique and computational power, are increasingly becoming easier to implement, allowing broader applications of the method. Future enhancements to geophysical models will increasingly focus on improving resolution and combining individual data sets to produce a fully 3-D model which is predictive of a range of observables.

RESEARCH ACCOMPLISHED

Surface Wave Models

Over the past several years, Lawrence Livermore National Laboratory (LLNL) has been developing surface wave models for nuclear explosion monitoring (Pasyanos et al., 2001; Pasyanos, 2005). Dispersion measurements are made using multiple narrow-band filters on deconvolved displacement data from the LLNL Seismic Research Knowledge Base (SRKB). We continue to improve upon our surface wave model by adding more paths by taking advantage of new data sets and also by revisiting stations with more recent events. Most recently, we have added measurements from stations in Alaska and Canada, Siberia, southern and central Africa, and southeast Asia. To date, over 120,000 seismograms have been analyzed to determine the individual group velocities of 7-150 second Rayleigh and Love waves. Overall, we have made good quality dispersion measurements for 41,000 Rayleigh and 30,000 Love wave paths. Using a conjugate gradient method, we then tomographically invert these measurements to produce group velocity maps for Love and Rayleigh waves.

The group velocity models have been enhanced in several ways. First, with more measurements, we have been able to expand the region of coverage from Eurasia and North Africa both south to include all of Africa and north (over the pole) to include the northern parts of North America (Figure 1 and Figure 2). In these extended regions, path coverage (in particular crossing ray paths) is sufficient for intermediate periods where we have many measurements, but we currently do not have sufficient coverage for high resolution at shorter periods where some features are smeared. We anticipate improvement at these periods with additional dispersion measurements. Path coverage throughout the broad region has been further improved by the use of cross-correlation of ambient seismic noise to derive the Green function between two stations, and from which the dispersion characteristics can be derived (Ritzwoller et al., these Proceedings). The benefits of this method in seismology have been dramatically demonstrated for southern California in Shapiro et al. (2005). Path maps for Europe (from Yang et al., 2007) are illustrated in Figure 3.



LLNL Seismic Research Knowledge Base (SRKB).

Figure 1. Surface wave dispersion maps for 20 second Rayleigh waves. (a) Path map showing coverage of the Eurasian and African continents. (b) Group velocity map of the same region (Pasyanos, 2005).

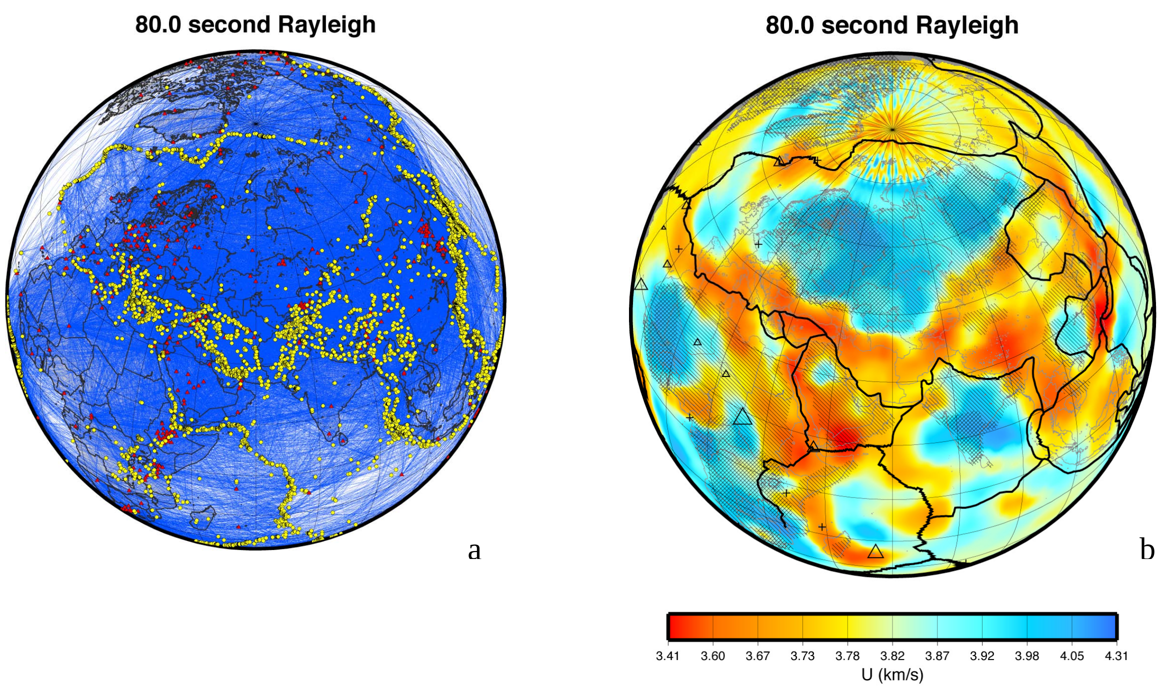


Figure 2. Surface wave dispersion maps for 80 second Rayleigh waves. (a) Path map showing coverage of the Eurasian and African continents. (b) Group velocity map of the same region (Pasyanos, 2005).

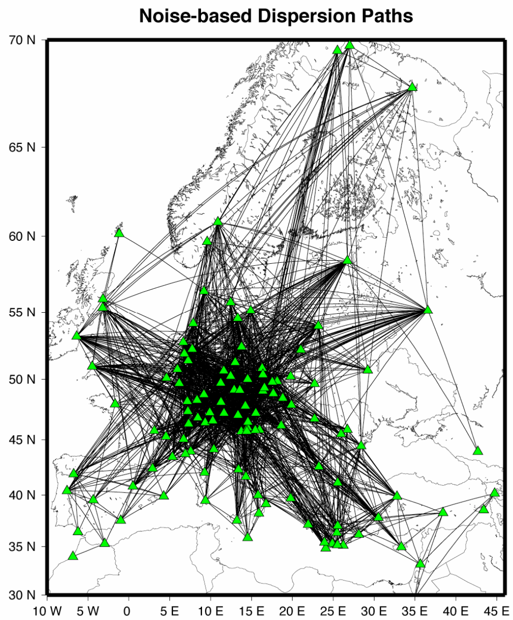


Figure 3. Cross-correlation path map for Europe. Stations are indicated by green triangles (measurements from Yang et al., 2007).

Velocity Models

One application of the surface wave models is to invert the dispersion results to derive models of the crust and upper mantle structure. This is particularly useful in aseismic regions that are poorly sampled by other data sets. Recently, we have used surface wave dispersion maps to construct a 3-D lithospheric velocity model of Africa and Arabia (Pasyanos and Nyblade, 2007), most of which is aseismic and not well-sampled by body waves. A crustal thickness map of the region is shown in Figure 4a. In North Africa, there is a crustal thickness contrast between the West Africa Craton and the East Saharan Shield. There is crustal thinning along the African Rift Systems (West and Central, as well as the East African Rift). In central and southern Africa, crust is consistently thick, although it appears to be thickest under the Congo Craton. Figure 4b shows a slice through the model at 200 km showing the faster velocities under the West African, Congo, and Kalahari Cratons in northern, central, and southern Africa, respectively.

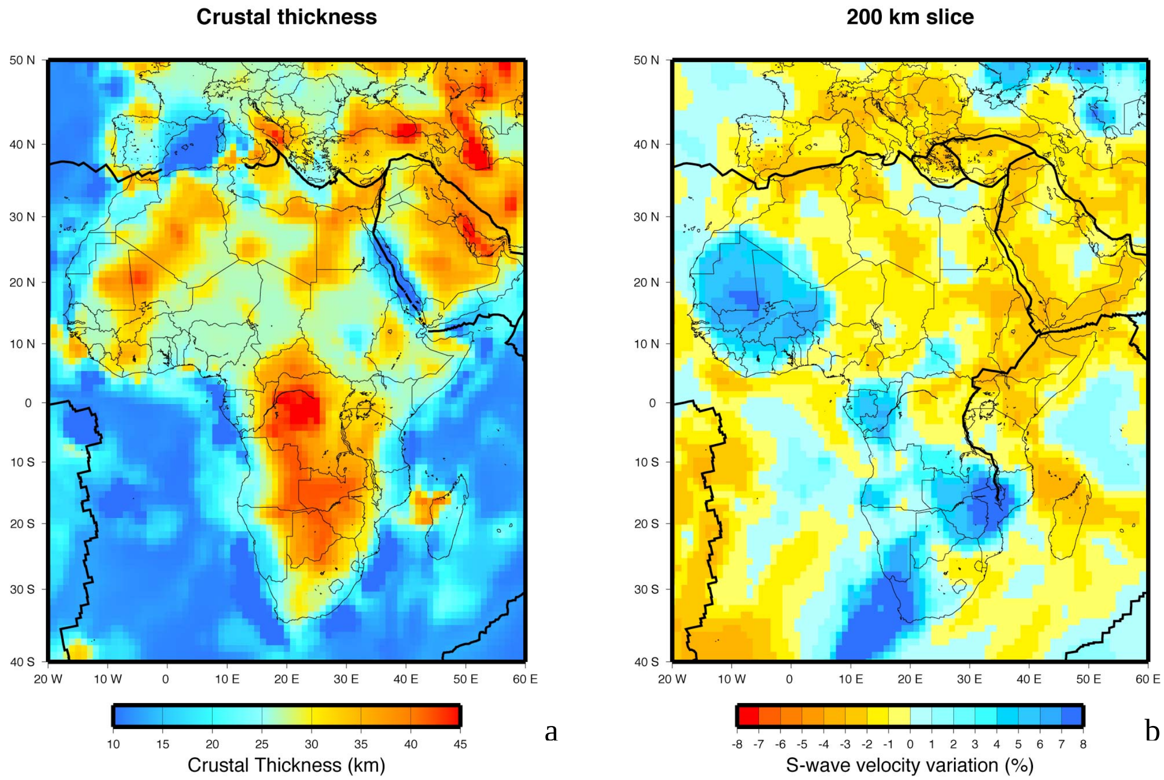


Figure 4. a) Crustal thickness map of Africa. b) S-wave velocity variation in the mantle under Africa at 200 km depth (from Pasyanos and Nyblade, 2007).

By applying the inversion of surface waves for structure to broad regions we can start to map out important tectonic features. For example, the velocities of long period surface waves are sensitive to the thickness of the lithosphere, which have been inverted for in Figure 5. Slower group velocities at short periods indicate the lack of a thick lithospheric lid and the presence of a slower, asthenospheric mantle not far below the crust. These are found at plate boundaries whether subducting convergent (Mediterranean, Japan), orogenic convergent (Turkish-Iranian Plateau, Himalayas), or divergent (Red Sea, oceanic rifts). Fast velocities at long periods indicate the presence of a thick lithospheric lid, as well illustrated by the lithospheric keels found under platforms and shields such as the West African Craton, Congo Craton, Indian Shield, South China Craton, Baltic Shield, Ukrainian Shield, and Russian Platform.

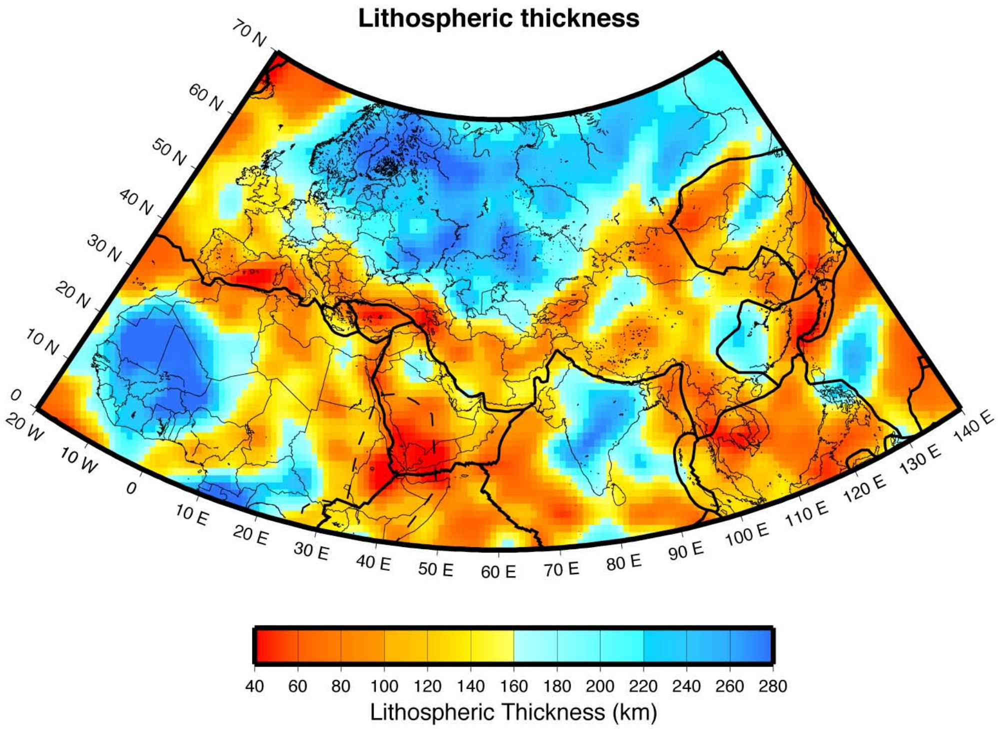


Figure 5. Lithospheric thickness map of Eurasia and North Africa. Plate boundaries are indicated by the solid black lines.

Regional Applications

We have used the surface wave models, mostly in conjunction with other data sets such as receiver functions, to produce regional velocity models. Recent studies have covered Arabia (Tkalcic et al., 2006), Kenya (Benoit et al., 2006), Kuwait (Pasyanos et al., 2007), eastern Turkey (Gok et al., 2007a), eastern Mediterranean (DiLuccio and Pasyanos, 2007), Iraq (Gok et al., 2007b), India and South Africa.

As an example, the KUW1 model was derived from the joint inversion of receiver functions and surface wave group velocities at station KUW in Kuwait. It is a 45 km thick crust with 8 km of sediments and very slow upper mantle velocities. Figure 6 shows how the KUW1 model (indicated by the solid blue line) compares to other models. In particular, we compare this velocity model to models determined from the simultaneous relocation of local seismic events using VELEST. These VELEST models do not have sensitivity in the shallow sediments and deep crust, but the resulting velocity profiles (shown by the red, brown, and black colored dashed lines) are very similar to the KUW1 model in the middle crust, regardless of various starting models, indicating that the KUW1 is also applicable for locating regional events. The preferred VELEST model (where the sedimentary column and deep crust are set to KUW1) is indicated by the solid purple line. The resulting models have significantly thicker crust than the current model used by the Kuwait National Seismic Network (KNSN), shown in green.

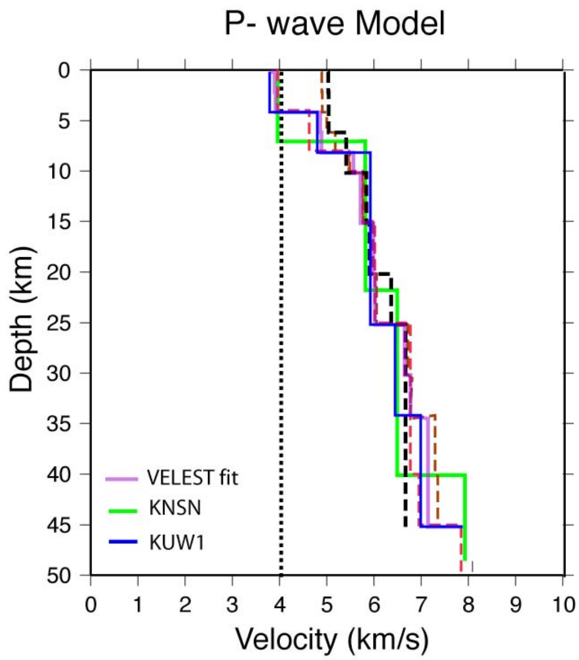


Figure 6. P-wave velocity profiles for Kuwait. See text for details (Pasyanos et al., 2007).

While the model can simultaneously fit surface waves, receiver functions, and local travel times, the model does not appear appropriate for regions not too distant from the station. Figure 7 shows the travel times of local Kuwaiti events and regional phases (Pn, Pg, Sn, Lg) from events in Iran recorded at station KUW, paths which primarily sample the Zagros Mts. The model fits reasonably well the local events (<1° distance) and the near regional events (3-4°), but the far regional events which have longer paths through the Zagros require faster upper mantle P-wave velocities and slower crustal P-wave and S-wave velocities.

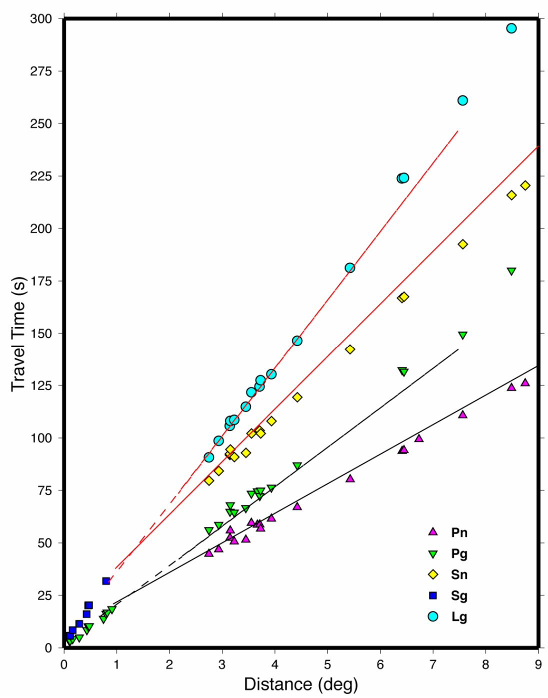


Figure 7. Travel times from local events and regional events in the Zagros recorded at station KUW in Kuwait (Pasyanos et al., 2007).

A Priori Models

The WENA model is an a priori three-dimensional model for Western Eurasia and North Africa (Pasyanos et al., 2004). Models like WENA can serve as background values for travel time correction surfaces and other derived parameters. In the original publication, we demonstrated our ability of the WENA model to predict a variety of data sets, including surface wave dispersion maps and matching crustal thickness estimates from receiver functions. In a followup paper, it was also demonstrated that it is also possible to improve regional travel-time prediction and seismic event location accuracy using this model (Flanagan et al., 2006). The authors conclude that a priori models are directly applicable where data coverage limits tomographic and empirical approaches, and the development of the uncertainty model enables merging of a priori and data-driven approaches using Bayesian techniques.

This model continues to evolve in several ways. First, the WENA model was joined with a Los Alamos model for Eastern Eurasia to produce a single model for Eurasia and North Africa (dubbed the Unified model). Secondly, crustal thicknesses in the model have been replaced by a 1-degree crustal thickness model derived from kriging thousands of individual crustal thickness estimates. The model continues to be tested and validated, recently to provide the best 1-D velocity profiles for waveform modeling.

Most recently, the attenuation structure of the model is being updated to replace the original placeholder values that were provided for crystalline crust and uppermost mantle layers. These updates will better reflect the tectonic history of the geophysical province (e.g., orogenic zone vs. shield) and allow the attenuation predictions of the model to more closely match those from empirical attenuation studies, such as those derived from Lg coda (e.g., Mitchell et al., 1997).

Stochastic Geophysical Models

In recent years, LLNL has been developing and refining the use of the Markov Chain Monte Carlo (MCMC) method to generate three-dimensional, data-driven stochastic earth models. We use MCMC to sample models from a prior distribution, test them against multiple data types in a staged approach, and develop a posterior distribution of seismic models that are most consistent with multiple seismic data sets (Pasyanos et al., 2006). This approach has several advantages over a single deterministic model. First, we are able to easily incorporate prior information on the model, such as the a priori geophysical models that were discussed earlier. Secondly, with this technique, we are able to reconcile different data types (such as body waves and surface waves) that can be used to constrain the model. We can also estimate the uncertainties of model parameters, properly migrating data uncertainties into model uncertainties. Finally, we can estimate uncertainties on predicted observable signals, such as would be required to apply this model as a correction surface.

While this approach has several advantages over deterministic models, the application of the method can be computationally expensive, allowing model development only in high-performance computing environments. For example, the application of this method to determine the crust and upper mantle structure of the Yellow Sea and Korean Peninsula (YSKP) region using surface wave dispersion data, body wave travel time data, gravity, and receiver functions has necessitated the use of Livermore Computing (LC) machines like Thunder, a 23 tflops peak-performance 1024 Node cluster where all nodes are 4-CPU, 1.4 GHz Itanium 2 "Madison Tiger4" nodes (see Figure 8). As we wish to apply this methodology to even broader regions with significantly larger data sets, one key objective has been to increase the efficiency of our runs. Over the past six months, we have solved some of the technical problems with increasingly larger data sets and have sped up the calculations significantly, allowing us to apply this to bigger problems.

Figure 8. Livermore Computing (LC) cluster Thunder.

Stochastic models represent one way of transitioning to 3D models, although there are a number of different approaches. Methods that developed separately are starting to converge. Surface wave models are increasing in resolution, allowing detailed shallow structure models. Body wave models have increasingly sophisticated modeling of the ray path, allowing more data to constrain the model. Data sets and computational power are both growing rapidly. On June 6-7, 2007, in Berkeley, CA, LLNL hosted the "Workshop on Multi-Resolution 3D Earth Models to Predict Key Observables in Seismic Monitoring and Related Fields" (Harris et al., these Proceedings). Questions raised during the workshop, such as model representation, data used to construct the model, operational constraints, uncertainties, etc., all have a significant effect on the best approach.

CONCLUSIONS AND RECOMMENDATIONS

Geophysical models play an important role in nuclear explosion monitoring, allowing us to capture the effect of the earth on seismic signals in a compact and self-consistent manner. As the availability of seismic data continues to expand and computational power rapidly grows, we have increasing power to truly image the high-resolution features of the earth that are necessary to support nuclear explosion monitoring operations. We have presented a variety of models currently being developed at LLNL. As data availability and computational power increase the models can be enhanced and combined in an effort to produce fully 3-D models.

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